In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. The present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail so as to not unnecessarily obscure the present invention.

Introduction

As noted above, the present invention provides a way to combine GaN technology with abundantly available Si substrates and mature Si processing technology for improved GaN-based device fabrication. A Si substrate is implanted an ionic species capable upon annealing of forming bubbles stable to the processing conditions of the device fabrication method. In a specific embodiment, He is the implanted species, although others, such as H or Ne (or other elements from group VIII) are also possible. For the case of Ne, and heavier implanted ions, the implants may be performed with the sample heated in order to avoid the substrate amorphization. After the implantation, the Si surface is cleaned using conditions that do not cause dissipation of the implanted ions or bubbles formed therefrom to the Si substrate surface. In the case of He, the cleaning is conducted at a relatively low temperature; below 300° C.; preferably room temperature.

A GaN/Si interfacial buffer layer is then grown on the cleaned Si substrate so that a buffer/Si interface is formed. A common GaN/Si buffer layer material is Al/N, although other materials that promote adherence/nucleation of the GaN to the Si may alternatively be used. The buffer layer growth process is generally a thermal process that also accomplishes annealing of the Si substrate so that bubbles of the implanted ion species are formed in the Si at an appropriate distance from the buffer/Si interface so that the bubbles will not migrate to the Si surface during annealing, but are close enough to the interface so that a strain field around the bubbles will be sensed by dislocations at the buffer/Si interface and dislocations are attracted by the strain field caused by the bubbles and move into the Si substrate instead of into the buffer epi-layer. A layer of GaN (or other III-Nitride based on GaN, such as InGaN or AlGaN) is then grown on the buffer layer.

The growth of the buffer and GaN-based layers any be accomplished by any suitable technique. Molecular Beam Epitaxy (MBE) is a suitable technique for accomplishing the relatively low temperature growth required for the He implantation embodiment of the invention. Metal-Organic Chemical Vapor Deposition (MOCVD) may be a suitable technique where low processing temperatures are not required, such as when H or Ne (or other elements from column VIII) are implanted. Another suitable low temperature film growth technique applicable to the present invention is Energetic Neutral Atomic-Beam Lithography/Epitaxy (ENABLE); this technique is described by Miller et al. [14], the disclosure of which in this regard is incorporated herein by reference.

In accordance with the invention, since the strain due to the lattice mismatch has been substantially dissipated by the misfit dislocations directed into the Si substrate, the GaN growth layer can grow with a substantial decrease of structural defects. In this way, strain relaxation at the buffer/Si interface can lead to the formation of larger grains than those observed in the GaN/AlN layers grown on un-implanted Si under the same conditions. Some dislocations will still likely remain in the GaN/AlN layer mainly due to the difference between the thermal expansion coefficient between Si and the layers grown on top of it. However, the distribution of the remaining dislocations in the AlN/GaN layers is uniform throughout the wafer, as opposed to laterally or pendeo-epitaxially overgrown layers, which are also able to decrease defect density in GaN (or other III-Nitrides based on GaN, such as InGaN or AlGaN) grown on foreign substrates. Therefore, in the present approach, the devices can be uniformly distributed.

He Implantation Embodiment

In a specific embodiment, He is implanted into the Si substrate with appropriate implant conditions. The implant conditions are selected to guide the implanted ions to concentrate about 100-250 nm, or preferably 120-200 nm, for example about 120 nm, from the Si substrate surface. Implantation energy of about 15-30 KeV and a fluence of 1 or 2×10^{16} cm^{-2} can produce acceptable implant results.

After the implantation, the Si surface is cleaned using conditions that do not cause dissipation of the implanted ions or bubbles formed therefrom to the Si substrate surface. Such a cleaning procedure does not involve a high temperature (e.g., greater than 800° C., such as about 1000° C.) hydrogen anneal, such has been performed in the growth chamber to ensure removal of any surface oxides remaining following a chemical clean. Cleaning in accordance with the present invention is conducted at a relatively low temperature, below 300° C., for example, about 80° C., or even room temperature. A RCA standard clean process [13], generally conducted at about 80° C., followed by dipping of Si samples in diluted HF solution and immediately loading into the growth chamber has been found to be suitable. In accordance with the present invention, this wet chemical cleaning process has been found to provide suitable wafer cleaning for high quality epitaxial growth of GaN on Si without the need for a high temperature anneal of the Si substrate in the growth chamber.

Since the thermal stability of the He bubbles is within 350-750° C., this low temperature cleaning technique is important to achieve the beneficial results according to this embodiment of the invention.

Then, an AlN buffer layer is formed on the Si substrate at a relatively low temperature of about 380-750° C., for example 680° C. Simultaneously this AlN growth temperature also serves to anneal the implanted Si substrate. At this temperature, the implanted He ions coalesce into He bubbles at a specific distance from the Si substrate surface (being determined by the implantation fluence and energy) such that misfit dislocations formed at the AlN/Si interface can interact with strain field formed around the He bubbles. Under these conditions, the He bubbles form neither too close nor too far from the Si surface, in which case they could either dissipate to the surface or be too far from the newly formed misfit dislocations for their strain fields to interact with them, respectively. The dislocations thus primarily move into the Si substrate (as threading dislocations) instead of into the AlN epi-layer.

Finally, the GaN layer of interest (or other III-Nitrides such as InGaN or AlGaN) is grown on the AlN surface. Molecular Beam Epitaxy (MBE) is a suitable technique for accomplishing the relatively low temperature growth required for this embodiment of the invention.

The beneficial result is thus achieved by appropriate control of the He fluence, distance of He bubbles from the Si surface and thermal parameters of the cleaning procedure of the Si before AlN growth and annealing during AlN growth.

As depicted in FIG. **1**(*a*) (i), a Si substrate is implanted with He with appropriate implant conditions. The implant conditions are selected so that the implanted ions are concentrated about 100-250 nm from the Si substrate surface, or preferably 120-200 nm, for example about 120 nm, from the Si substrate